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THREE-DIMENSIONAL STRUCTURE OF THE EXTENDED SOLAR MAGNETIC FIELD AND THE SUNSPOT CYCLE VARIATION IN COSMIC RAY INTENSITY

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Three Dimensional Structure of the Extended Solar Magnetic Field and the Sunspot Cycle Variation in Cosmic Ray Intensity

by

Leif Svalgaard
and
John M. Wilcox

March 1976

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INSTITUTE FOR PLASMA RESEARCH
STANFORD UNIVERSITY, STANFORD, CALIFORNIA

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A principal cause for the eleven-year sunspot cycle variation in the primary cosmic ray intensity observed at earth may be a variation in the solid angle of the heliosphere occupied by the extended solar polar magnetic fields. We assume that galactic cosmic rays have relatively easy access to the inner solar system through the regular extended solar polar fields, and relatively difficult access through the irregular extended solar sector structure fields.

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Leif Svalgaard
John M. Wilcox
Institute for Plasma Research
Stanford University
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The interplanetary magnetic field within several astronomical units of the sun appears to have one polarity in most of the hemisphere north of the solar equatorial plane and the opposite polarity in most of the hemisphere south of the equatorial plane.[1-7] The two hemispheres are separated by a curved current sheet that typically crosses the solar equatorial plane in either two or four places, thus dividing the equatorial region into either two or four sectors. Near sunspot minimum, at one astronomical unit the extent in latitude of the curved current sheet is typically $\pm 15^{\circ}$, so that the sector boundary (the current sheet separating the two hemispheres of opposed field polarity) is almost parallel to the solar equatorial plane. In the photosphere, on the other hand, the sector boundary makes an angle of approximately 90° with the equatorial plane.[8] At 1.5 solar radii, in 1972 and 1973, the angle between the sector boundary and the equatorial plane was approximately 45°,[9] and at 3 to 10 solar radii the angle between boundary and plane was approximately 25°.[10] A schematic of this structure for the case of four sectors is shown in Figure 1.

In the photosphere, near sunspot minimum, the sector magnetic fields cover a range in latitude of typically $\pm 40^{\circ}$,[8] while at one astronomical unit the comparable range in latitude has been compressed to perhaps $\pm 15^{\circ}$. How is this compression in latitude accomplished? A typical magnitude of the sector magnetic fields in the photosphere is 0.5 gauss (P.H. Scherrer and T.L. Duvall, personal communication). This is a measure of the large-scale field that will dominate in the region a few solar radii above the photosphere,

where the smaller-scale but much stronger fields associated with active regions do not reach. In the polar regions of the sun the large-scale uni-directed photospheric field has a typical magnitude of perhaps 5 gauss (R. Howard, personal communication). Thus, at one or two solar radii above the photosphere, and above the region of influence of active regions, the magnetic pressure associated with the solar polar regions is two orders of magnitude larger than the magnetic pressure associated with the equatorial sector structure. This will compress the equatorial sector field structure into a narrow range of latitudes. This effect can be clearly seen in the sketch in Figure 2 made from an eclipse photograph taken at solar minimum in 1954.[11]

During an interval near sunspot maximum, when the solar polar field polarities are reversing, the magnitude of the polar fields may be considerably less, and the resulting compression of the equatorial field structure also much less. The sector structure fields may then occupy a much larger fraction of the heliosphere. Since the sector structure fields reverse polarity typically four times or two times per solar rotation, a galactic cosmic ray headed toward the sun may encounter considerably more magnetic scattering from the complex sector structure field than from the uni-directional field that fills most of each solar hemisphere near sunspot minimum. This geometrical effect may be the principal cause of the eleven-year modulation of cosmic ray intensity observed at earth, since the solar wind velocity[12] and the magnitude of the interplanetary field[13] observed near earth have not changed very much during the present sunspot cycle.

The fraction of the heliosphere occupied by sector structure fields as a function of time through an average sunspot cycle can be estimated in the following way. Because the current sheet shown in Figure 1 is warped with respect to the solar equatorial plane, during the half-year when the earth is north of the equatorial plane an interplanetary sector with the same polarity as the northern solar polar region is observed to be wider than it would be if observed when the earth is in the equatorial plane of

the sun. For example, assume that there are two sectors per solar rotation and that the extent in heliographic latitude of the sector structure near the earth is ± 20°. When the earth is at a latitude near 7°N (i.e. near September 7), the sector whose polarity is the same as the northern polar region will be observed to last 16.5 days, as compared with the 13.5 days it would last if observed when the earth is near the solar equatorial plane. For comparison, if the extent in heliographic latitude of the sector structure near the earth is ± 45°, then the sector with the same polarity as the northern polar region will have a length of 14.6 days when observed near the earth at 7° north. We see that if we measure the magnitude of this Rosenberg-Coleman effect[14,15] through a sunspot cycle we can estimate the extent in heliographic latitude of the sector structure.

We have used a harmonic analysis to compute the average amplitude of the Rosenberg-Coleman effect as a function of years from the time of sunspot minimum for the four sunspot cycles whose minima were near 1934, 1944, 1954 and 1965. Interplanetary field polarities inferred from polar geomagnetic variations[16] were used, and the resulting amplitude of the Rosenberg-Coleman effect was multiplied by 1.43 to correct for the approximately 85% accuracy[17,18] of the inferred interplanetary field polarities.

Figure 3 shows the resulting value for the extent in heliographic latitude of the sector structure through an average sunspot cycle. Three-year running means were used to reduce the scatter. Year 0 is the average of the sunspot minimum years 1934, 1944, 1954 and 1965. The effect of uncertainties in the computation of the magnitude of the Rosenberg-Coleman effect will usually be to decrease the amplitude of the effect and, therefore, the latitude values shown in Figure 3 should be considered upper limits. We may expect considerable variation from the average effect shown in Figure 3, and in particular for intervals of several months near sunspot minimum the current sheet may occupy only a few degrees of latitude. As a first approximation to the sunspot cycle variation of cosmic ray intensity observed at earth resulting from the varying geometry described by Figure 3, we may consider that galactic cosmic rays have relatively difficult access to the inner solar system in the portion of the heliosphere occupied by the changing fields of the sector structure, and relatively easy access through the portions of the heliosphere

occupied by the extended solar polar fields. In Figure 4 we show the solid angle of the heliosphere occupied by the extended solar polar fields through an average sunspot cycle, where the latitude angles shown in Figure are used to compute the solid angles shown in Figure 4.

Also shown in Figure 4 are the monthly averages of the absolute intensity of primary cosmic rays of rigidity greater than 0.5 GV observed near Murmansk and at Mirny from 1958 to 1973.[19] The total flux of such galactic cosmic rays in the interstellar medium in the vicinity of the earth is estimated to be 4000 m^{-2} sec^{-1} $ster^{-1}$.[19] Therefore, in Figure 4 we have set the total solid angle 4π of the heliosphere as equivalent to a flux of 4000 m^{-2} sec^{-1} $ster^{-1}$, and the zero of the solid angle scale corresponds to zero flux. This corresponds to the assumption that galactic cosmic rays have easy access to the inner solar system through the solid angle of the heliosphere occupied by the extended solar polar fields, and difficult access through the solid angle occupied by the sector structure fields.

In Figure 4 we see that the average sunspot cycle variation of the solid angle of the extended solar polar fields is rather similar to the observed variation of the flux of primary cosmic rays of rigidity greater than 0.5 GV during 1961 to 1969. We should not expect a detailed agreement between the computed variation of solid angle averaged over four sunspot cycles and the observed cosmic ray flux around a single sunspot minimum. The similarity of the two curves in Figure 4 suggests that there may be some validity to the considerations advanced in this paper. The detailed computation of the diffusion lengths of cosmic rays related to these considerations is beyond the scope of this paper.

Acknowledgements

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Figure Captions

Figure 1 Schematic showing the warped current sheet in the inner solar system (inside 6 AU). This current sheet divides the interplanetary magnetic field in the heliosphere into two regions with oppositely directed field lines. In one region the field polarity is away from the sun (at present this region is north of the solar equator), in the other region the field polarity is toward the sun. The situation is shown for a four-sector structure, i.e. as the current sheet is rotated past a stationary observer in the course of a solar rotation, the observer will see four changes of magnetic polarity, suggesting that the interplanetary magnetic field is divided into four sectors of alternating polarity. Where the current sheet lies above the solar equatorial plane it is shown by full lines, while dashed lines indicate that the current sheet is below the equatorial plane. The extent in latitude of the current sheet was assumed to be $\pm 15^{\circ}$. The sun at the center is not shown to scale.

Figure 2 The structure of a sunspot minimum solar corona drawn from eclipse photographs[11] (30 June 1954) obtained in Kozeletsk.

Figure 3 Computed variation of the average extent in heliographic latitude of the extended solar sector magnetic fields. Year 0 is the average of the sunspot minimum years 1934, 1944, 1954 and 1965. The value 20° on the ordinate means that the extended sector fields are in the interval 20°N to 20°S, etc.

Figure 4 Galactic cosmic ray intensities with rigity 0.5 GV observed near Murmask and at Mirny from 1958 to 1973.[12] Also shown is the computed average solid angle of the heliosphere occupied by the extended solar polar magnetic fields.

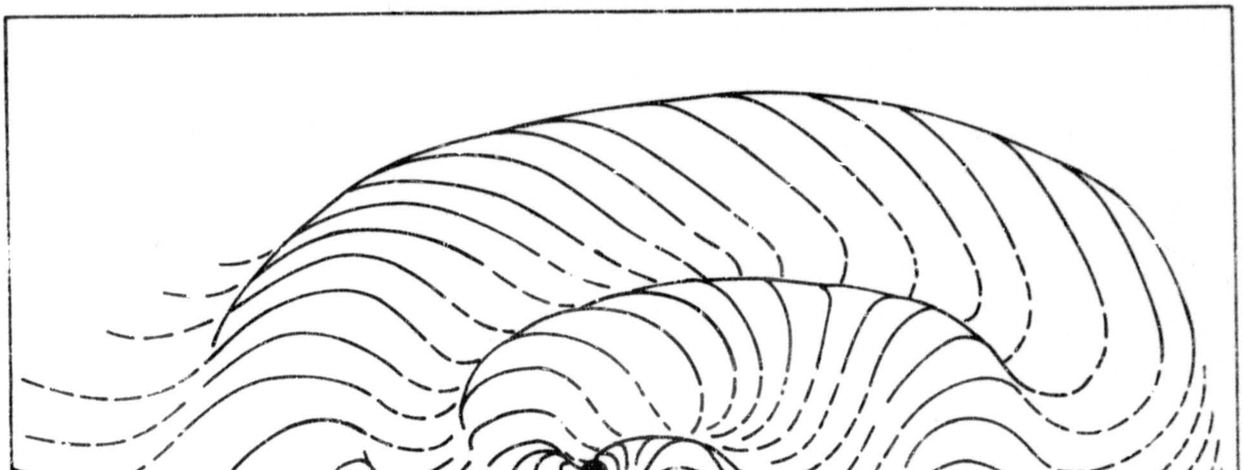


Figure 1

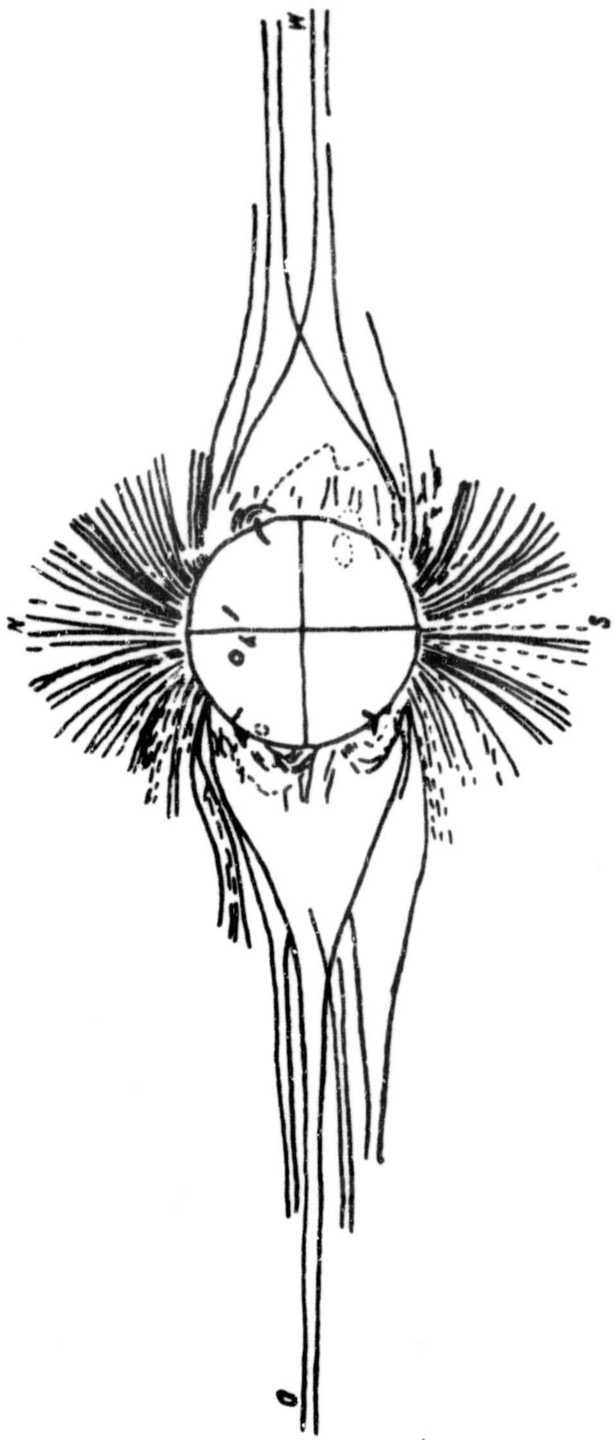


Figure 2

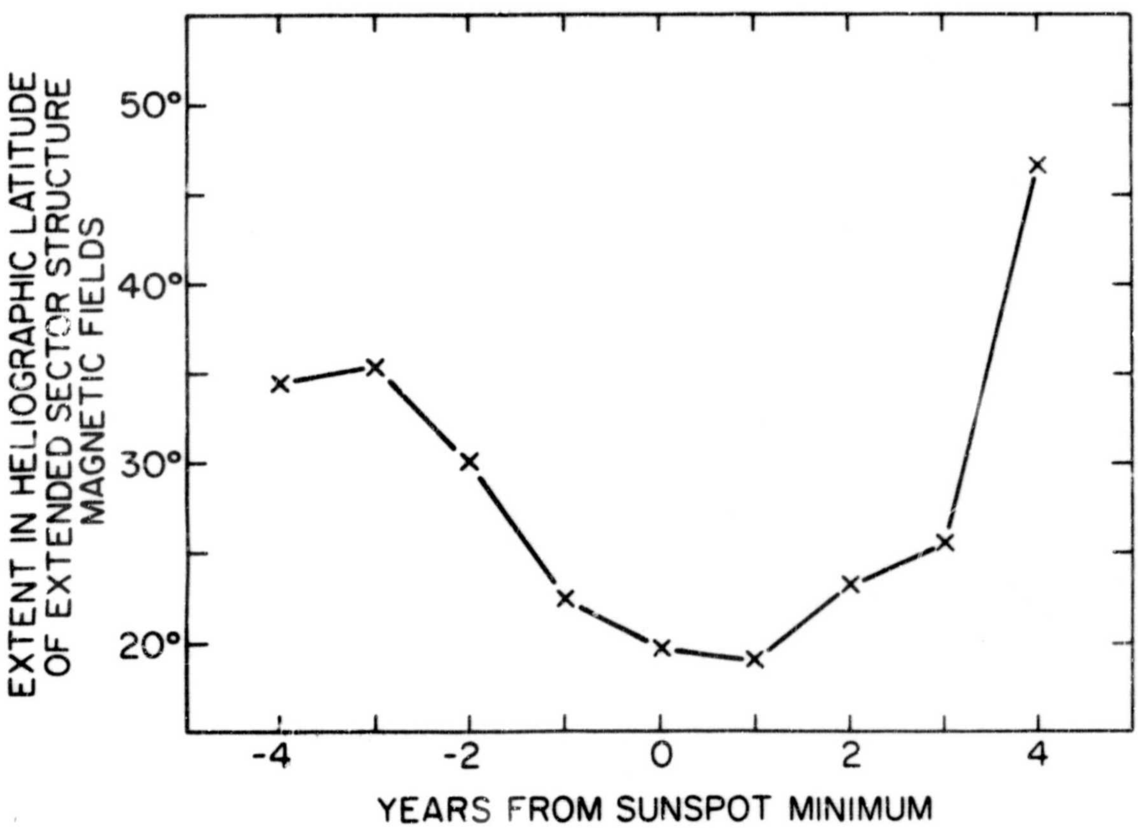
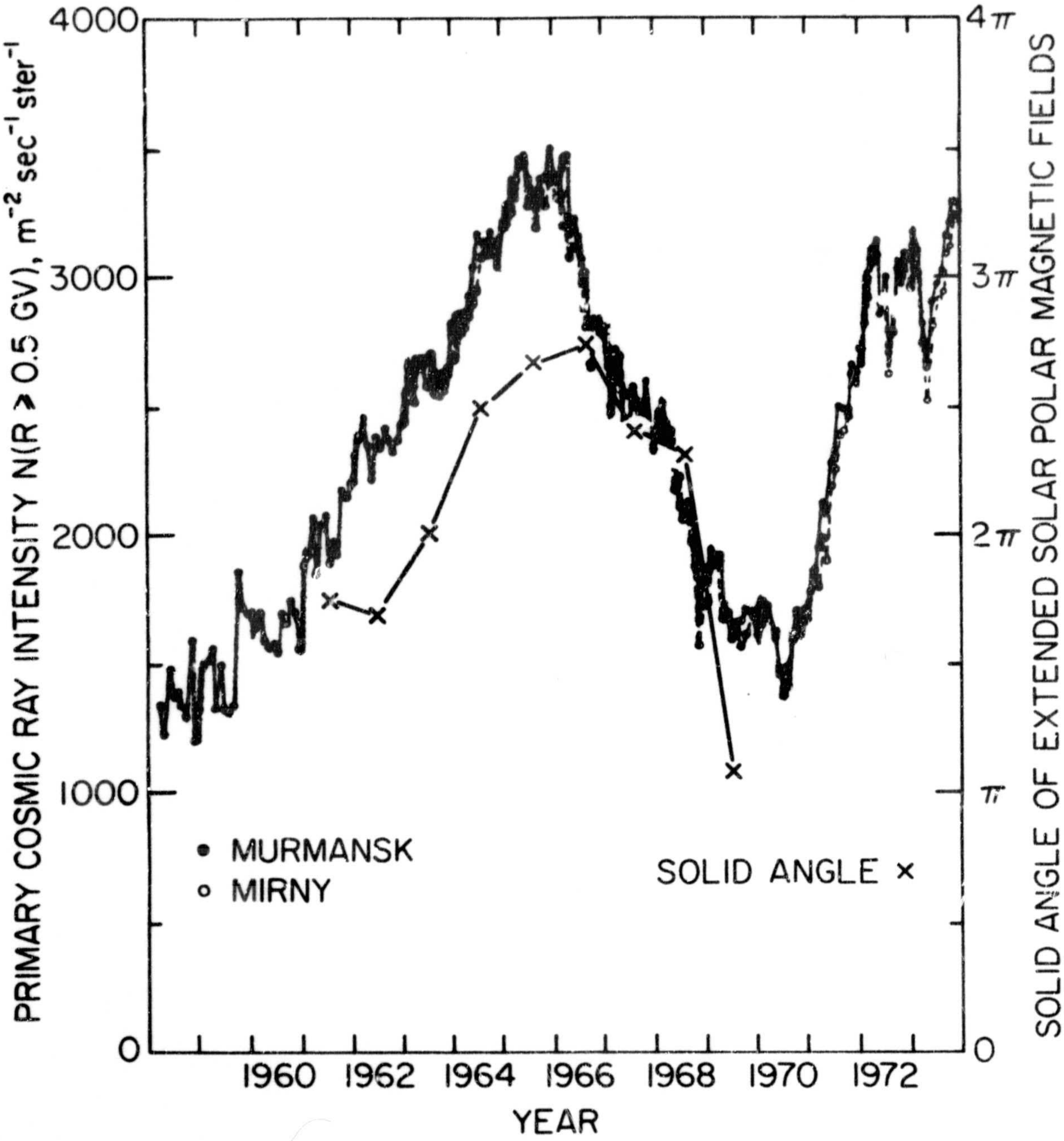

EXTENT IN HELIOGRAPHIC LATITUDE
OF EXTENDED SECTOR STRUCTURE
MAGNETIC FIELDS
50°
40°
30°
20°
-4
-2
0
2
4
YEARS FROM SUNSPOT MINIMUM

Figure 3



PRIMARY COSMIC RAY INTENSITY N(R ≥ 0.5 GV), $m^{-2}\,sec^{-1}\,ster^{-1}$
SOLID ANGLE OF EXTENDED SOLAR POLAR MAGNETIC FIELDS
4000
3000
2000
1000
0
4π
3π
2π
π
0
1960
1962
1964
1966
1968
1970
1972
YEAR
MURMANSK
MIRNY
SOLID ANGLE ×

Figure 4